Direct Phase-Resolved Simulation of Large-Scale Nonlinear Ocean Wave-Field

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LONG-TERM GOAL

The long-term goal is to develop a new powerful capability, which is named **SNOW** (**s**imulation of **n**onlinear **o**cean **w**ave-field), for predicting the evolution of large-scale nonlinear ocean wave-fields using direct phase-resolved simulations. Unlike the existing phase-averaged approaches, SNOW models the key mechanisms such as nonlinear wave-wave, wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation in a direct physics-based context.

OBJECTIVES:

The specific scientific and technical objectives are to:

1. Implement a powerful High-Order Spectral (HOS) capability on parallel HPC platform for phase-resolved computations of large-scale nonlinear ocean wave-field evolution including nonlinear resonant and long-short wave-wave interactions

2. Develop a robust capability of modeling wave-breaking dissipation for phase-resolved simulation of large-scale ocean wave evolutions

3. Develop physics-based models for phase-resolved simulation of nonlinear wave-current interactions, wave focusing and blocking by variable current, and nonlinear wave diffraction/reflection/refraction by bottom topography

4. Develop a robust capability for the generation of proper initial wave-field conditions based on (i) discrete wave elevation data; and/or (ii) satellite or radar images of ocean surface; and/or (iii) specified wave spectrum for phase-resolved simulation of nonlinear ocean waves

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5. Validate the developed capabilities and models by direct quantitative comparisons to theory and laboratory/field measurements

6. Study nonlinear evolution of ocean wave spectra using direct phase-resolved simulations and make quantitative assessments of phase-averaged wave-prediction models

7. Investigate the mechanics and criteria for the development of three-dimensional wave breaking using phase-resolved computation of large-scale nonlinear wave-field evolutions

APPROACH

SNOW employs direct physics-based phase-resolved simulations for predicting the evolution of large-scale nonlinear ocean wave-fields. SNOW is fundamentally different from the existing phase-averaged models in that, under SNOW, key physical mechanisms such as wave-current, wave-wind and wave-bottom interactions and wave-breaking dissipation are modeled, evaluated and calibrated in a direct physics-based context. In SNOW, detailed phase-resolved information about the wave-field is obtained, from which the statistical wave properties can also be derived.

SNOW is based on a powerful high-order spectral (HOS) approach for direct phase-resolved simulations of nonlinear wave dynamics with direct physics-based models to include the effects of various physical processes such as wind input, wave interactions with variable current and bottom topography, wave breaking, and bottom dissipation. HOS is a pseudo-spectral-based method that employs the Zakharov equation and mode-coupling idea and accounts for nonlinear wave-wave, wave-current, and wave-bottom interactions to an arbitrary high order (M) in wave steepness. This method is extremely efficient as it obtains exponential convergence and linear computational effort with respect to the order (M) and the number of wave/bottom modes (N). HOS is an ideal approach for direct simulations of large space-time domain evolution of nonlinear ocean wave-fields. The efficacy of HOS for the study of mechanisms of nonlinear wave dynamics in the presence of atmospheric forcing (Dommermuth & Yue 1988), long-short waves (Zhang, Hong & Yue 1993), finite depth and depth variations (Liu & Yue 1998), and variable ambient current (Wu 2004) has been well established.

For data assimilation and/or specification of initial wave-fields for direct phase-resolved simulations, an effective nonlinear wave reconstruction algorithm is used. The objective of wave reconstruction is to obtain detailed specifications (including phase) of a nonlinear wave-field, which matches given wave probe and/or remotely sensed data, or a specified wave spectrum. The scheme for nonlinear wave reconstruction is based on the use of multiple-level optimizations with theoretical and computational solutions for the nonlinear wave dynamics. Specifically, the low-order analytic Stokes wave solutions are used for low-level optimizations while nonlinear HOS computations are used for high-level optimizations. These ensure a unique reconstruction of wave-fields with wave steepness up to ~90% Stokes limit. The validity of this methodology has been systematically verified by quantitative comparisons to laboratory measurements and synthetic wave data for both long- and short-crested irregular wave-fields (Wu, Liu & Yue 2000, Wu 2004).

For large-scale ocean wave-field evolution, SNOW computations are performed on high-performance computing platforms with O(102-3) processors.

WORK COMPLETED

The main focuses are on the development and improvement of effective physics-based wave breaking dissipation model, the validation of SNOW simulation of spectrum evolution against wave basic experiments and field experiments, and the speedup of computational algorithms for generating initial nonlinear wavefield from a given spectrum or radar sensed surface data, and for simulating large-scale nonlinear ocean wavefield evolutions on large parallel platforms. Specifically,

- ***Viscous dissipation model***: We investigated viscous dissipation effects on wave group instability and wave breaking development in long-time evolution of nonlinear wave trains (Wu, Liu & Yue 2006a, 2006b).

- ***Wave breaking mechanism and dissipation model***: We investigated the basic mechanisms governing the development of three-dimensional wave breaking phenomenon and developed effective physics-based models for SNOW for accounting for wave breaking dissipation in phase-resolved simulation of nonlinear wave-field evolution.

- ***Efficient algorithm for steep waves***: In order to account for fully nonlinear wave-wave interaction effects in steep wave-field evolution, we developed a highly efficient computational algorithm, so-called pre-corrected FFT method, based on the boundary-element method formulation and the use of FFT algorithm for efficient evaluation of influence coefficients (Yan, Liu, & Yue 2006). The PFFT algorithm is capable of accounting for fully nonlinear free-surface effects with ~O(N) computational effort.

- ***Modeling of stratified fluid and bottom topography effects***: We extended SNOW for phase-resolved wave-field evolution simulations to littoral zones including stratified fluid and bottom topography effects. An efficient algorithm based on the extension of HOS is developed to compute large-scale surface wave interactions with internal waves and bottom topography.

- ***Initial conditions for phase-resolved wave-field simulation***: We continued to develop and improve the data assimilation algorithm for initialization of a nonlinear wavefield from a given wave spectrum or in-situ measured and/or remote sensed wave data. In particular, a parallelized optimization algorithm is developed to improve the efficiency of nonlinear wave reconstruction using in-situ measured data and radar sensed surface data.

- ***Phase-resolved simulation of wave spectrum evolution***: We developed a parallelized Monte-Carlo simulation scheme to study the evolution of energy spectrum of nonlinear wave-fields using SNOW. At each moment during the evolution, the wave spectrum is obtained from an ensample average of a large number of wave-field realizations of given initial wave spectrum with different initial phases.

- ***Speedup of SNOW***: We continued to seek for high-performance computational resources to support the SNOW project. Last year, with 70K CPU-hours awarded as a DoD non-challenge project, we were able to constantly improve the computational speed and robustness of the SNOW code on advanced high-performance computing platforms.

RESULTS

Two representative results obtained using large-scale phase-resolved SNOW computations are reported here: (I) deterministic reconstruction of nonlinear wave-field conditions based on radar sensed surface profile; and (II) nonlinear evolution of directional wave spectra and comparisons to field measurements.

(I) ***Deterministic reconstruction and forecasting of three-dimensional wave-field evolution from radar sensed surface profile.*** Based on an instantaneous surface measurement (e.g. radar sensed ocean surface), we reconstruct phase-resolved kinematics and dynamics of the wave-field and use them as initial conditions of SNOW simulations to forecast the spatial and temporal evolution of the wave-field. The domain in which the wave-field evolution can be reliably predicted is completly determined by the wave properties extracted from the given data. A theory developed for determining the predictable wave-field region based on probe data (Wu 2004) can be directly extended to this case. Figure 1 shows a sample result of such wave reconstruction and forecasting using SNOW. For this example, wave elevation in the domain $x \in [0, 2000]$m and $y \in [0, 2000]$m at $t = 0$ is specified for wave reconstruction. This synthetic wave-field is generated based on a truncated JONSWAP spectrum (with Philips parameter α=0.0352, enhancement factor γ=3.3, and peak frequency ω_0 = 0.52s-1, and truncated at ω = 0.36s-1 and 1.06s-1) with a directional spreading function of $(2/\Theta)\cos^2(\pi\theta/\Theta)$ with $\Theta = \pi/6$ and $|\theta| \leq \Theta/2$ and random wave-component phases. The contours of the error of the reconstructed and forecasted wave-field (compared to the original specified wave-field) at three moments t =0s, 60s, and 120s are shown in figure 1, from which it is seen that the wave-field evolution within the predictable region is well predicted using SNOW based on the specified instantaneous wave profile data.

(II) Nonlinear Evolution of directional wave spectrum. Field measurements (Hwang *et al*. 2000) indicate that while angular spreading of ocean wave-fields is generally symmetric with respect to the dominant wave direction, the spreading becomes broader and changes from unimodal to bimodal as the wavenumber increases. In particular, bimodal distribution starts to develop for wavenumber slightly greater than ~2kp (corresponding to 1.4ω_0), and the angular separation between two distribution lobes increases for higher wavenumber. From SNOW simulations, we obtain similar features in nonlinear evolution of directional wave spectrum. Figure 2 shows the comparison between SNOW computations and the field observations (Hwang *et al*. 2000) of the dependence of angular spreading function on frequency/wavenumber. In SNOW simulations, the initial directional wave-field is generated from a JONSWAP spectrum with Philips parameter α=0.0352, enhancement parameter γ=1.0, peak frequency ω_0 = 0.52s-1, and a frequency-independent directional spreading function of $(2/\Theta)\cos2(\pi\theta/\Theta)$ with $\Theta = \pi$ and $|\theta| \leq \Theta/2$. For comparisons, the angular spreading functions averaged over four different frequency bands, $\omega<\omega_0$, $\omega_0\leq\omega<1.5\omega_0$, $1.5\omega_0\leq\omega<2\omega_0$, and $2\omega_0\leq\omega<2.5\omega_0$, at the initial time t=0 and after 100Tp (Tp=$2\pi/\omega_0$) of nonlinear evolution are shown in figures 2a and 2b. For the field data (Hwang *et al*. 2000), the angular spreading functions for k=kp, k=3kp, and k=5kp averaged over a two-hour periods are shown in figures 2c, 2d, and 2e, respectively. The comparisons between SNOW simulations and the field observation indicate that SNOW computations predict properly the dependences of angular spreading of wave spectra on wavenumber/frequency in nonlinear evolution of directional wave-fields.

IMPACT/APPLICATIONS

This work is the first step toward the development of a new generation of wave prediction tool using direct phase-resolved simulations. It augments the phase-averaged models in the near term and may serve as an alternative for wave-field prediction in the foreseeable future.

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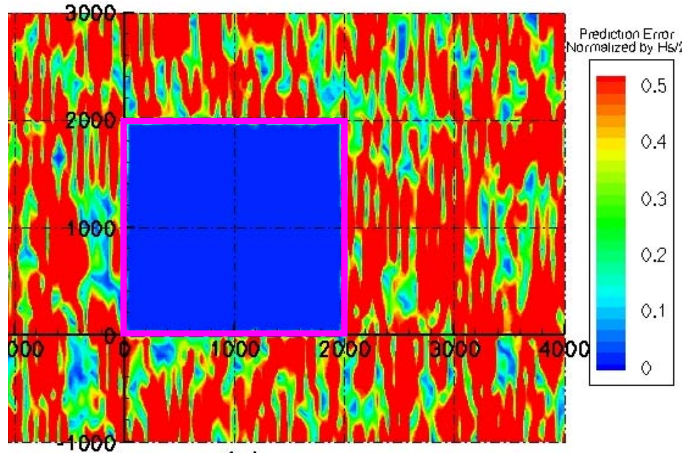
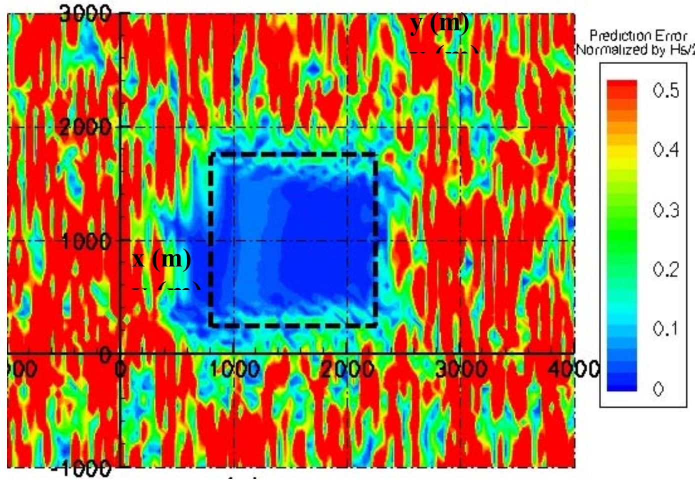
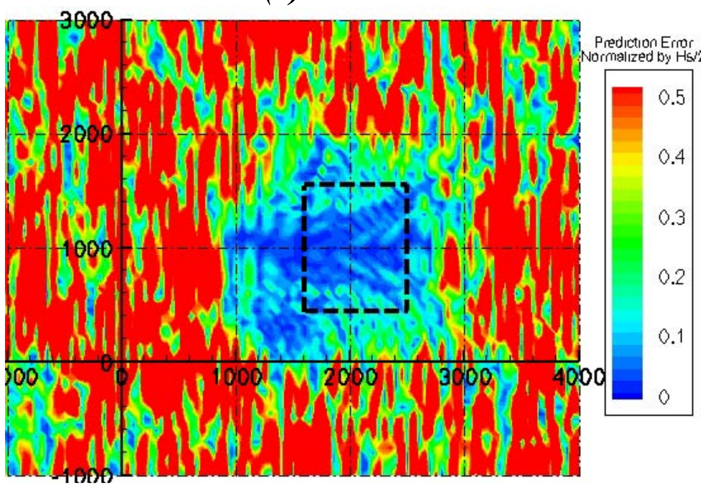


(a) t = 0s



(b) t = 60s



(c) t = 120s

Figure 1: Contours of the normalized error between the deterministically reconstructed/predicted wave-field and the original short-crested wave-field at three moments: (a) t = 0s; (b) t = 60s; and (c) t = 120s. The wave reconstruction is deterministic, based on the instantaneous wave profile data in the specified region $x \in [0, 2000]$ m and $y \in [0, 2000]$ m at t = 0s, which is enclosed by the purple line (——) in (a). The domains enclosed by the dashed line (- - - -) in (b) and (c) are the theoretical regions where phase-resolved wave-field information can be predicted at these moments.

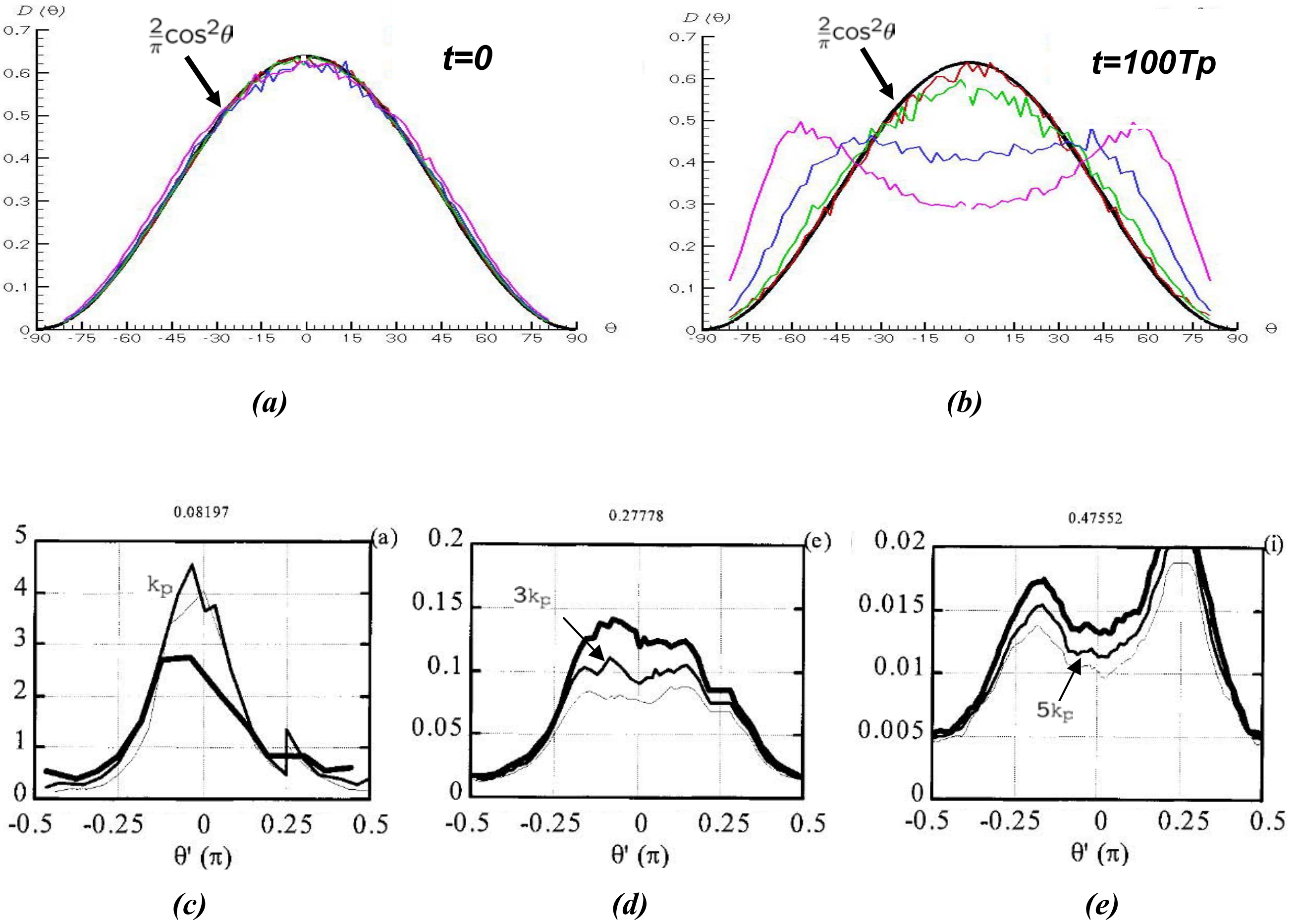


Figure 2: Qualitative comparison of angular spreading function of wave spectrum on frequency/wavenumber in the nonlinear evolution of directional (short-crested) ocean wave-field between SNOW computations, (a)-(b), and field observations (Hwang et al. 2000), (c)-(e). In SNOW simulations, the initial directional wavefield is generated from a JONSWAP spectrum with Philips parameter α=0.0352, enhancement parameter γ=1.0, peak frequency $\omega 0$ = 0.52s-1, and a frequency-independent directional spreading function of $(2/\Theta)\cos2(\pi\theta/\Theta)$ with $\Theta = \pi$ and $|\theta| \leq \Theta/2$. The plotted are the angular spreading function averaged over different frequency bands at the initial time t=0 (a) and after nonlinear evolution of 100Tp (b). The plotted curves in (a) and (b) are respectively cos2-spreading function (——) and angular spreading functions averaged for $\omega<\omega 0$ (——), $\omega 0\leq\omega<1.5\omega 0$ (——), $1.5\omega 0\leq\omega<2\omega 0$ (——), and $2\omega 0\leq\omega<2.5\omega 0$ (——). In field observations (Hwang et al. 2000), The angular spreading functions for k=kp, k=3kp, and k=5kp averaged over a two-hour periods are shown in (c), (d), and (e), respectively. The peak wave number is kp=0.098m-1 and the significant wave height is Hs=1.5m for the field data.